The Panchromatic View of Stellar Flares

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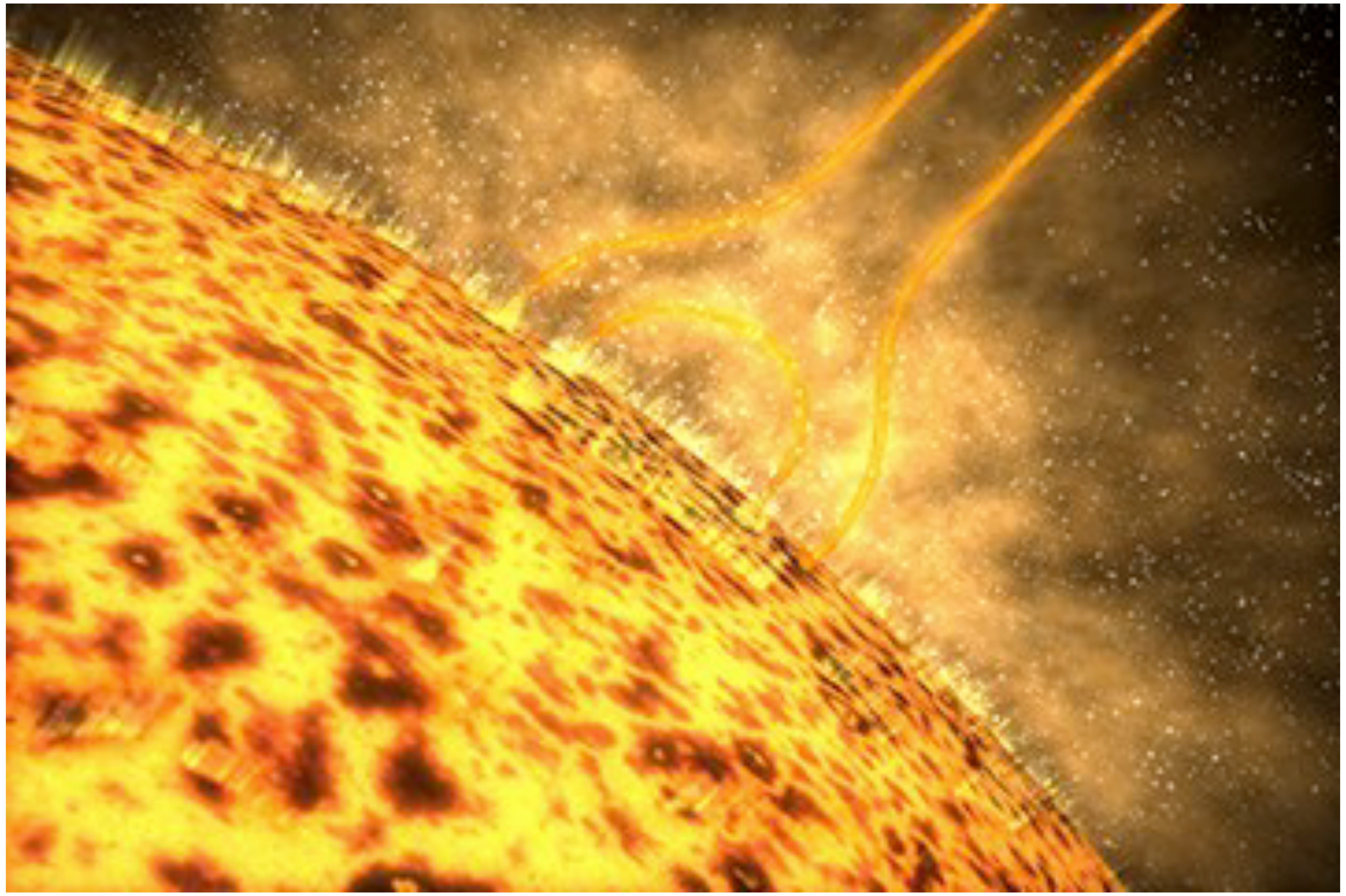
Outline

-What do you learn from studying flares at different wavelengths?

-Ways to accomplish multi-wavelength flare observations, lessons learned

-Some thoughts on coming CMB-S4 time domain potential for stellar flare science

Stellar Flares are Probes of Energy Release Processes

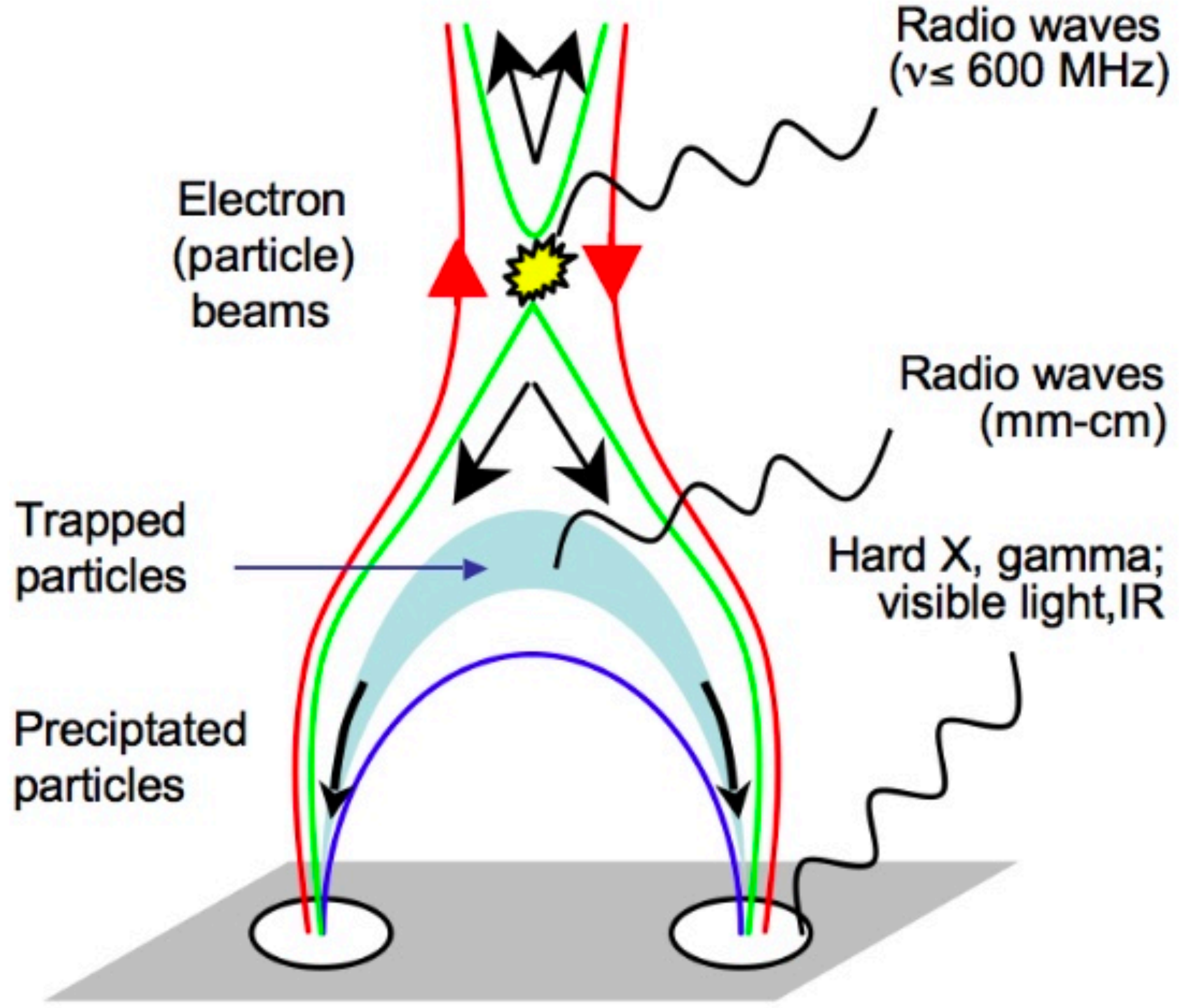


Flares:

- Involve particle acceleration, plasma heating, shocks, mass motions
- Are a consequence of magnetic reconnection occurring high in the corona
- Involve all layers of the atmosphere
- Produce emissions across the EM spectrum
- Are only one component of stellar magnetic eruptions (coronal mass ejections, energetic particles)

The Multi-wavelength Perspective

Observational Flare Signature	Solar	Stellar*
nonthermal hard X-ray emission	✔	?
radio gyrosynchrotron/synchrotron, dm-cm-mm wavelengths	✔	✔
coherent radio emission, m-dm-cm wavelengths	✔	✔
FUV emission lines (transition region)	✔	✔
optical/UV continuum (photosphere)	✔	✔
EUV/soft X-ray emission (corona)	✔	✔
optical emission lines (chromosphere)	✔	✔



Klein & Dalla (2017)

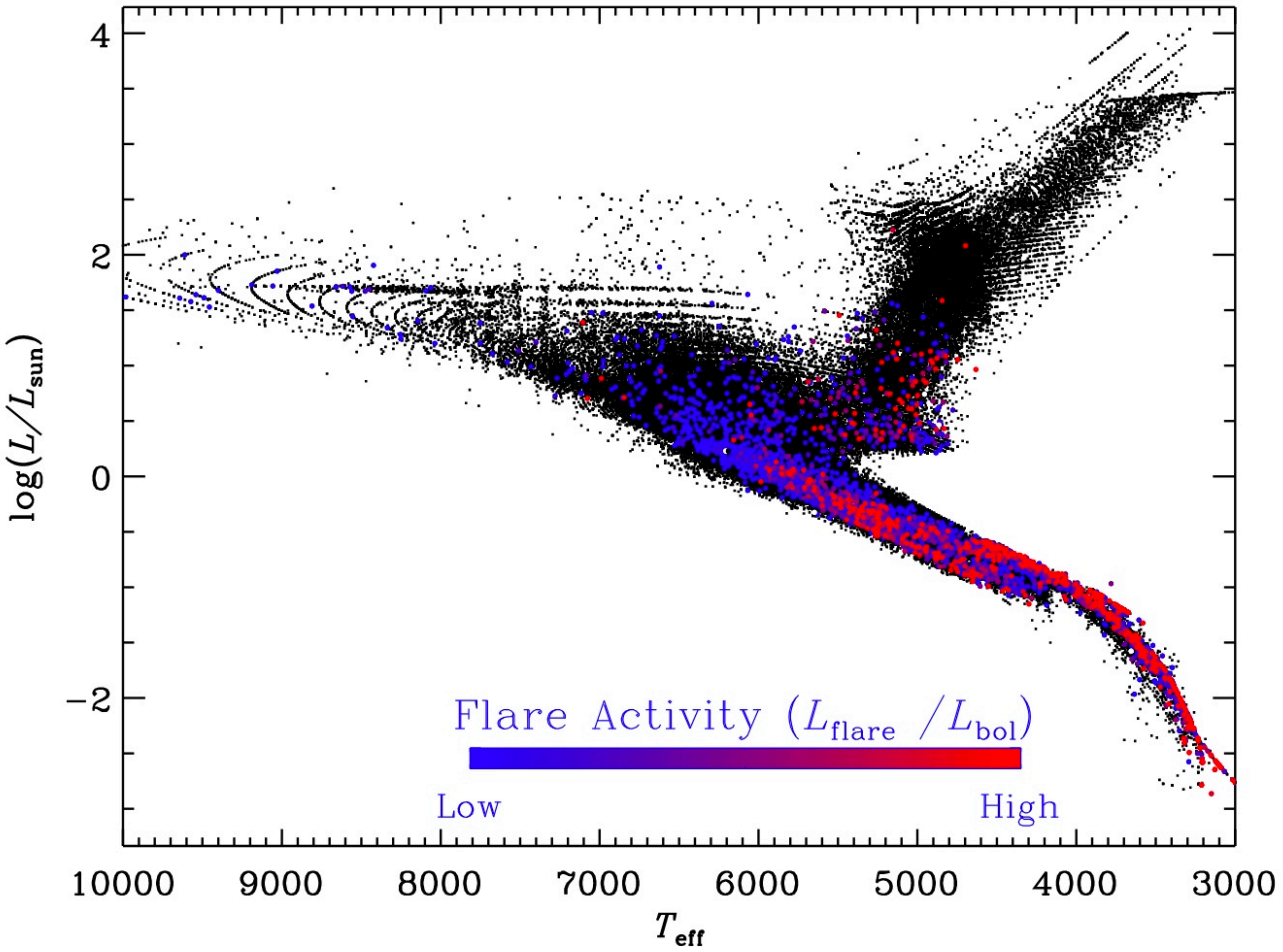
Osten (2016) in Heliophysics: Active Stars and their Astrospheres

*across different cool stars

Flares are a Fact of Life for Cool Stars on/near the Main Sequence

- Assume that the different physical processes involved in flares are universal
- Want to probe that assumption, examine any dependence on stellar parameters (age, stellar type, existence of companions, size of the flare)
- Flares influence the near-stellar environment, and are a factor in exo-space weather for other planetary systems

H-R Diagram of Flaring Stars

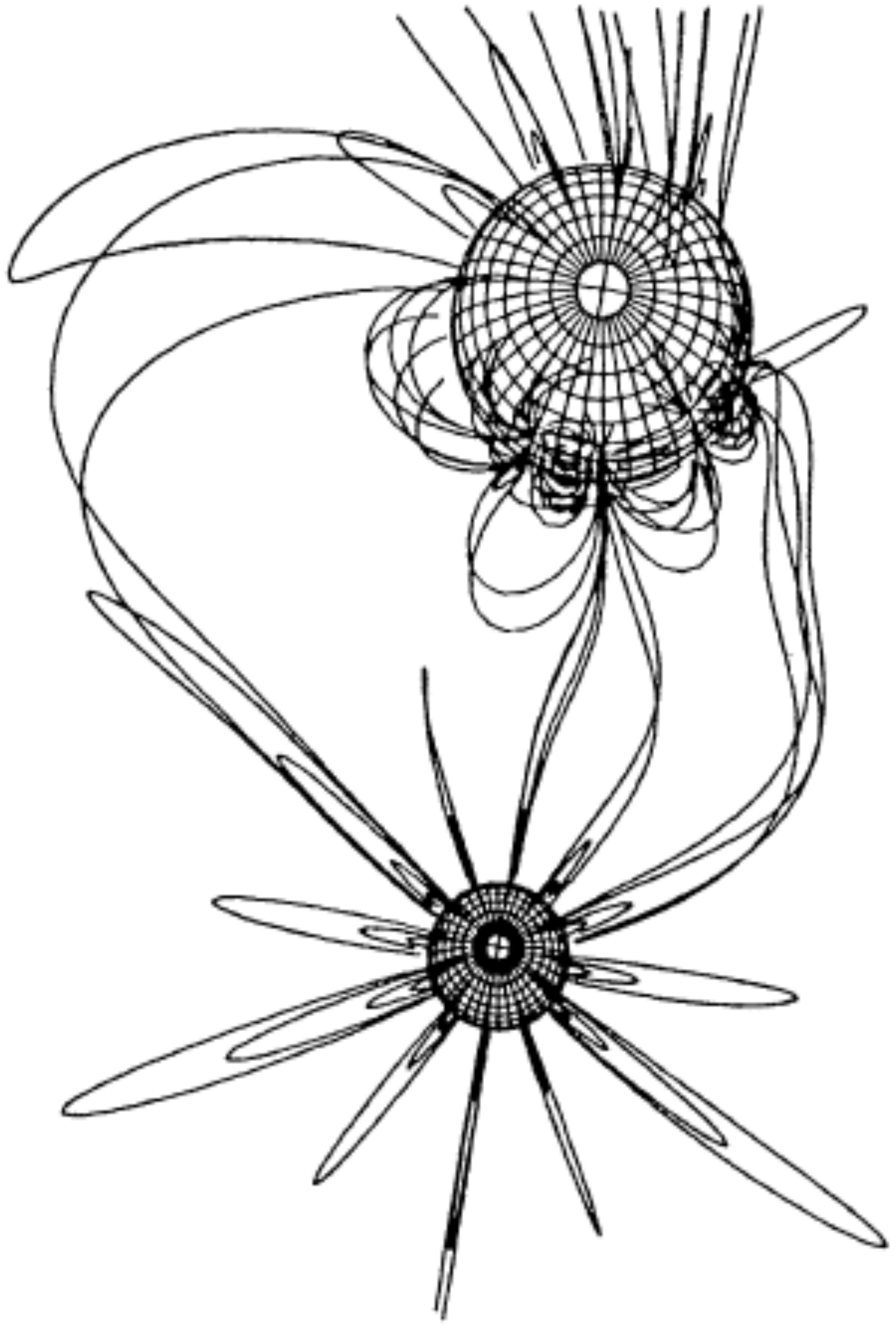


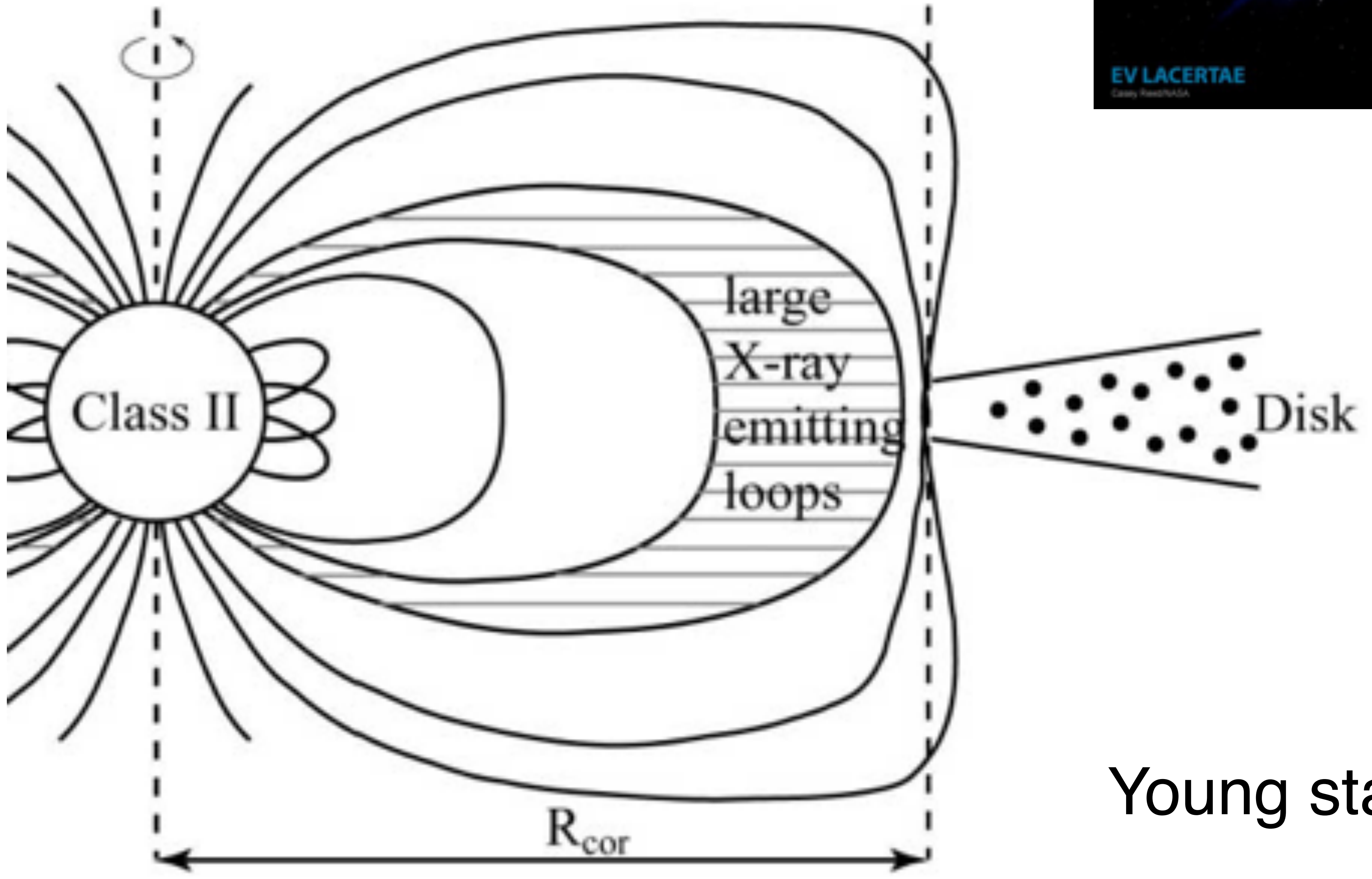
white light flaring from the Kepler mission: Yang & Liu 2019

The Usual Suspects: Flaring Stars With High Flare Rates, Extreme Flares

M dwarfs w/deep convective zones

Tidally interacting close binaries





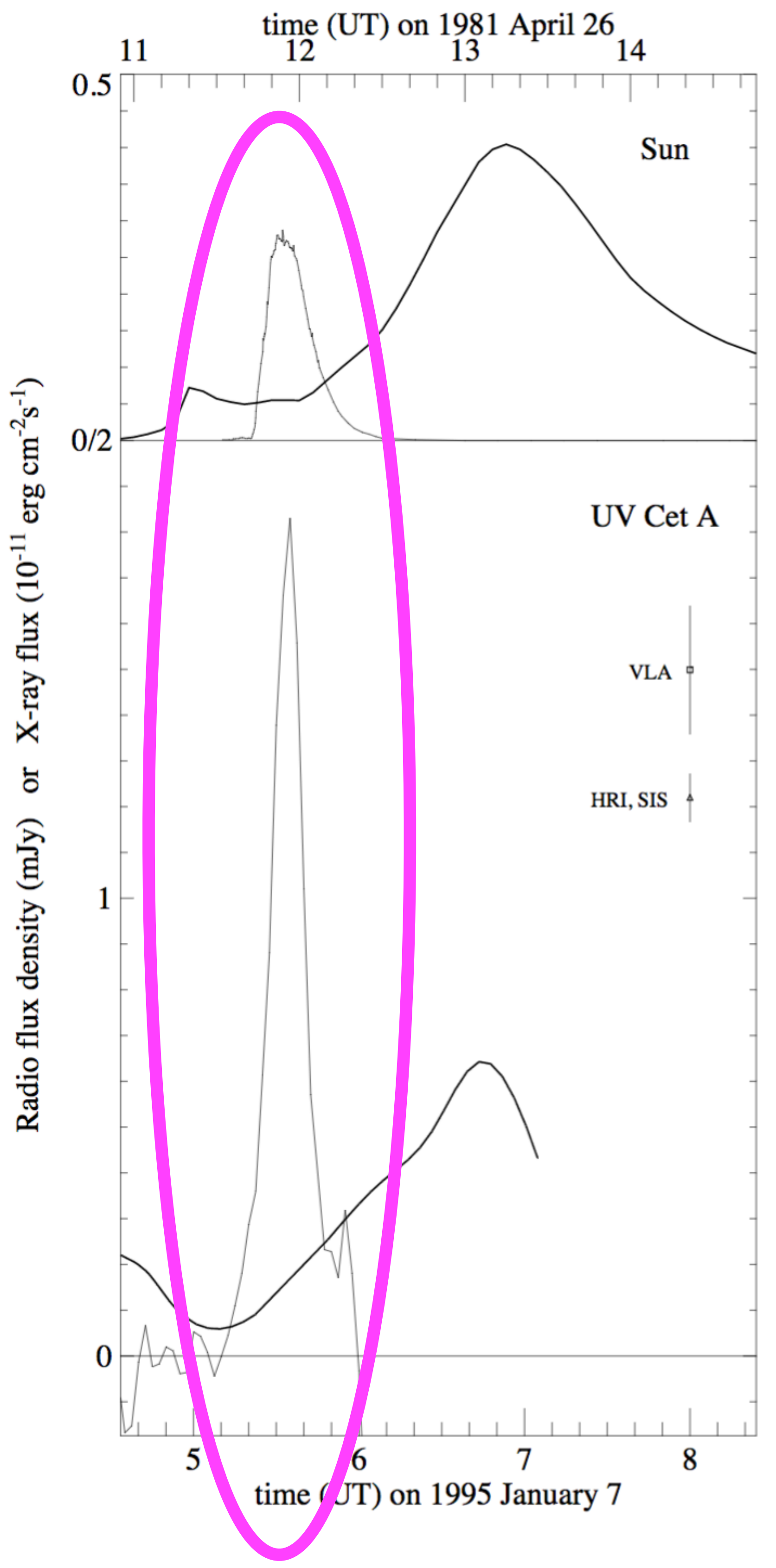
Young stars

Solar & Stellar Flares (Appear to) Have Similar Radiative Energy Partitions

	λ range	$f=E_{rad}/E_{bol}$ (Sun)	$f=E_{rad}/E_{bol}$ (active stars)*
GOES	1-8 Å	0.01[A]	0.06
coronal	0.01-10 keV	0.2[B]	0.3
hot blackbody	1400-10000 Å	0.7[C]	0.6
U band	3000-4300 Å		0.11
Kepler	4000-9000 Å		0.16

[A] Woods et al. (2004); [B] Emslie et al. (2012); [C] Kretzschmar et al. (2012); *Osten & Wolk (2015)

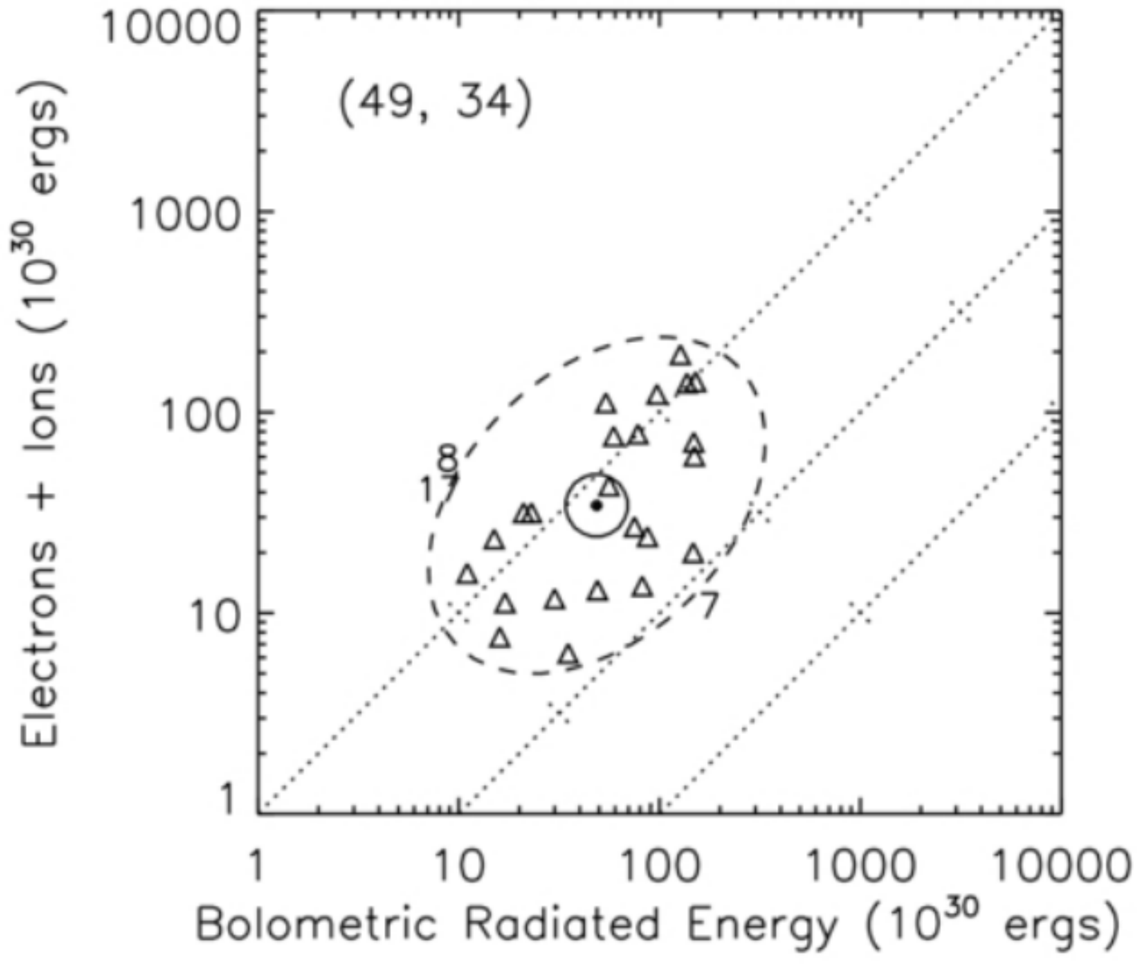
But Dissimilar Accelerated Particle Characteristics?



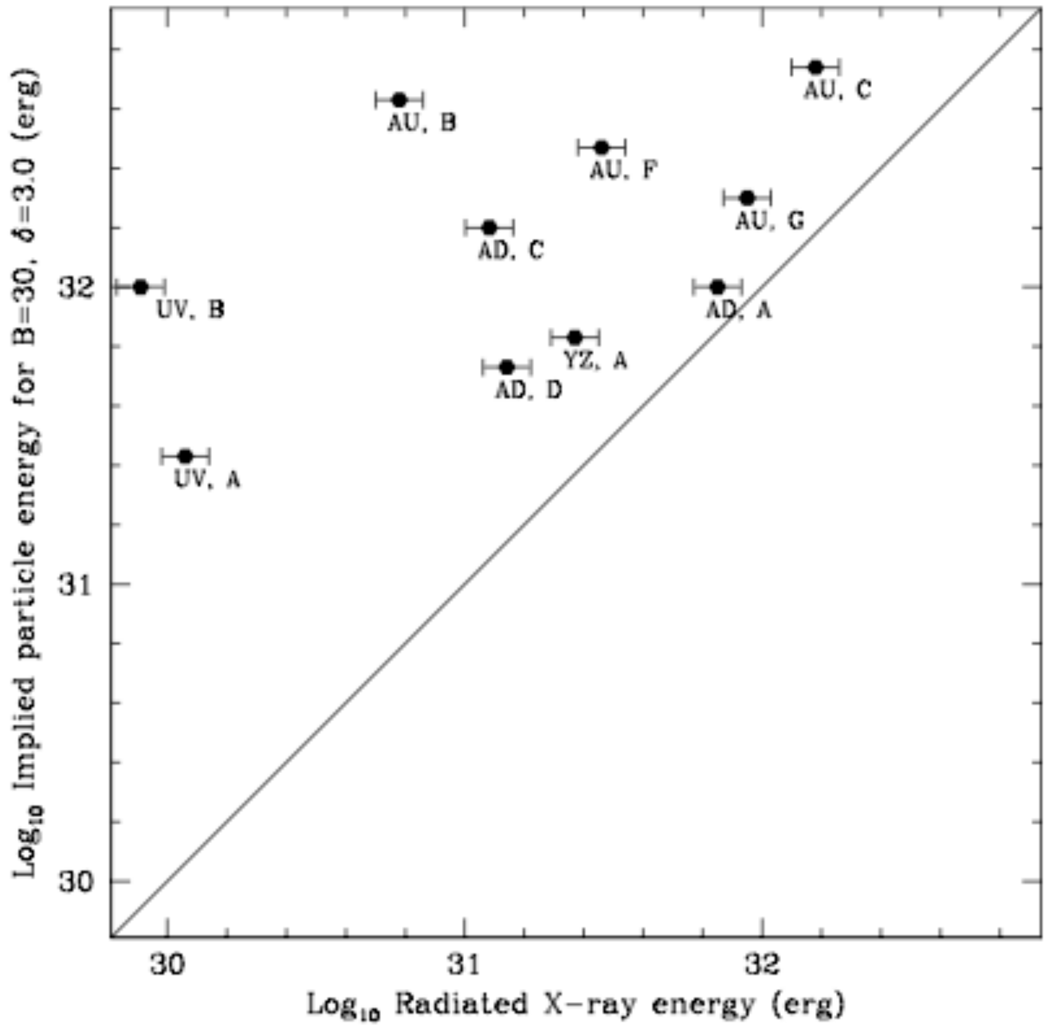
Güdel et al. (1996)
M dwarf X-ray-radio flare
compared to solar

➡Stellar flare cm-wavelength radio emission comes from gyrosynchrotron emission from accelerated particles

Relative to the flare X-ray emission, stellar flares produce larger radio amplitudes than for solar flares (Güdel et al. 1996)



solar eruptive events,
~ equal amounts of energy
Emslie et al. (2012)



M dwarf flares
more energy in non thermal particles than in corona
Smith et al. (2005)

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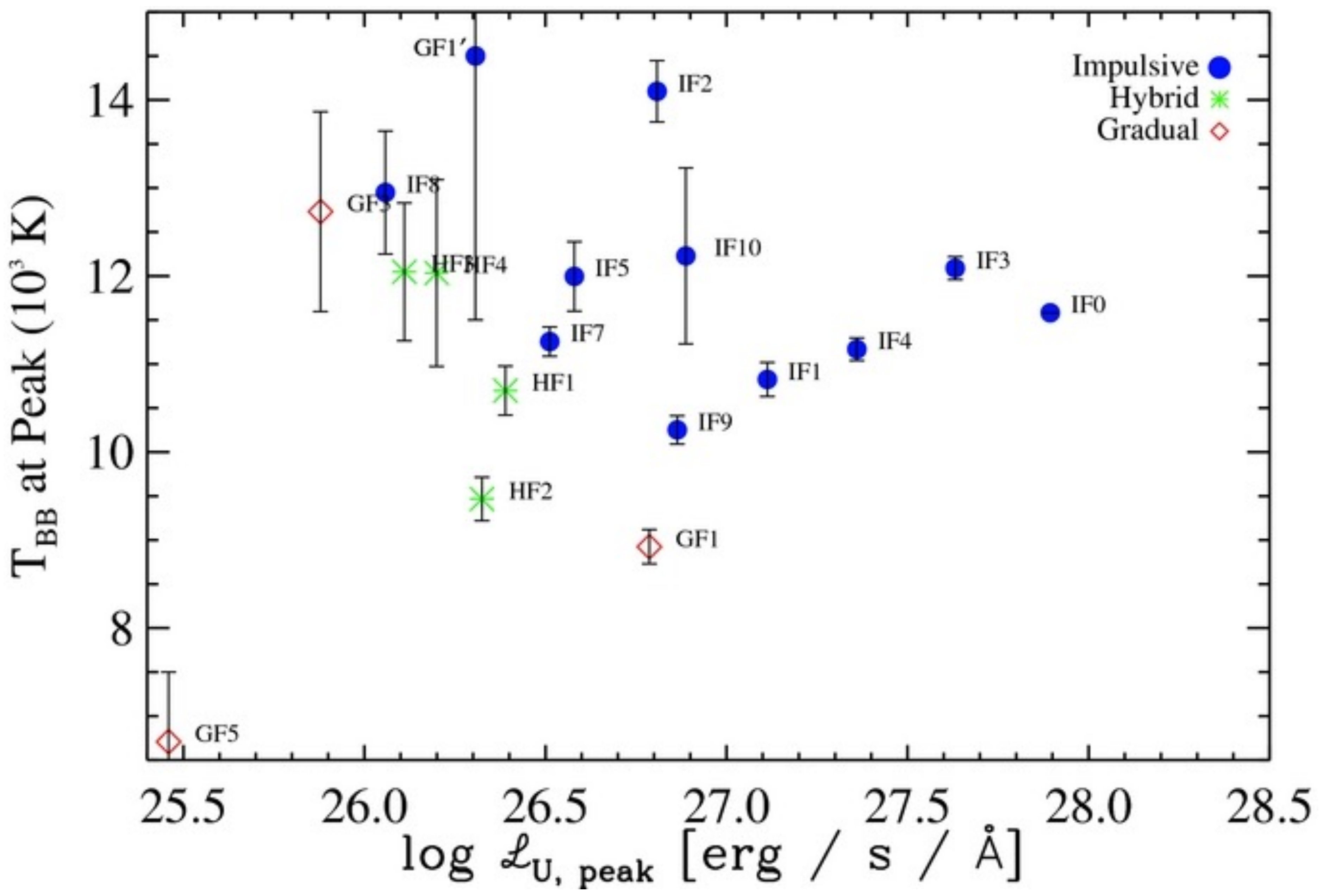
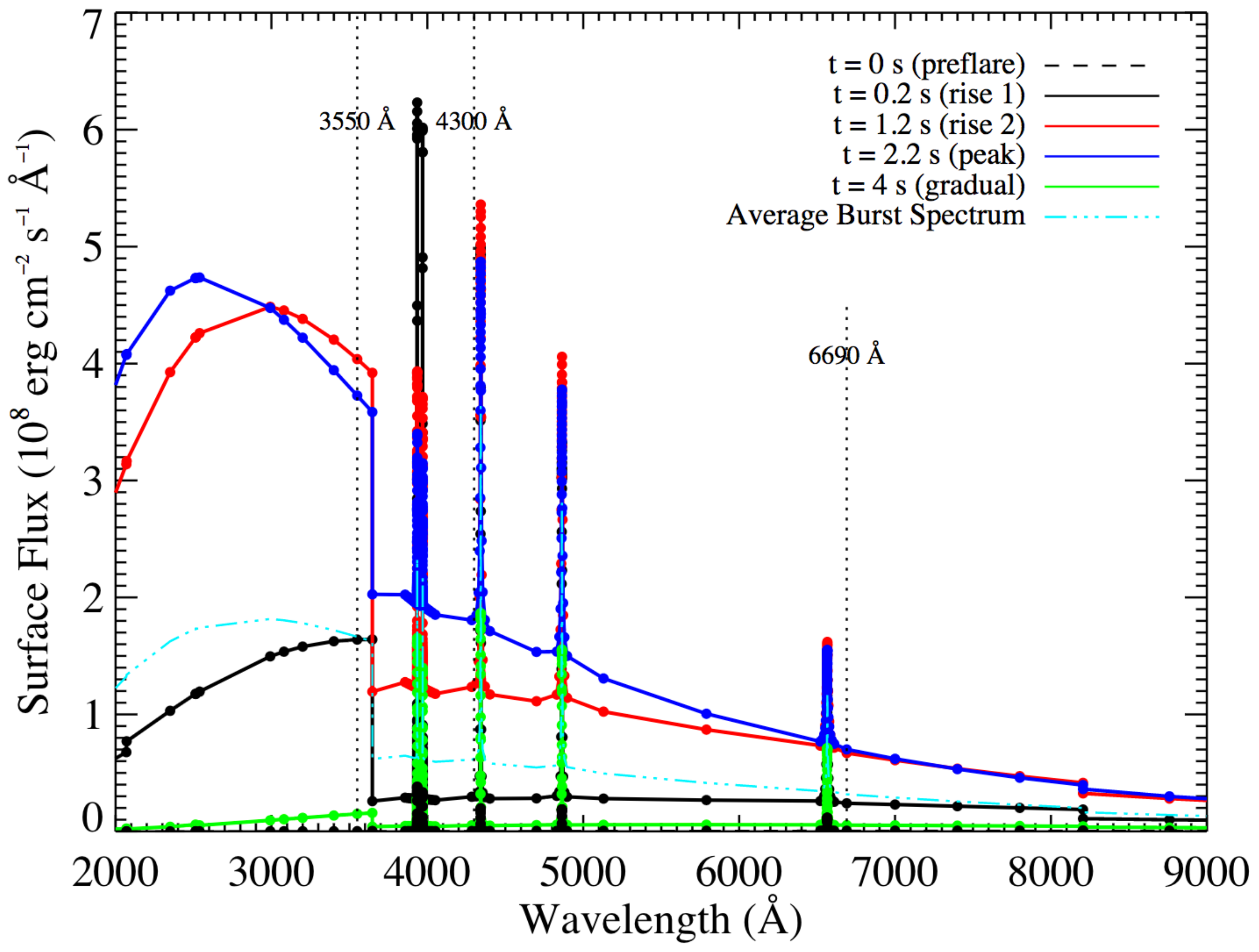


Kowalski et al. (2013)

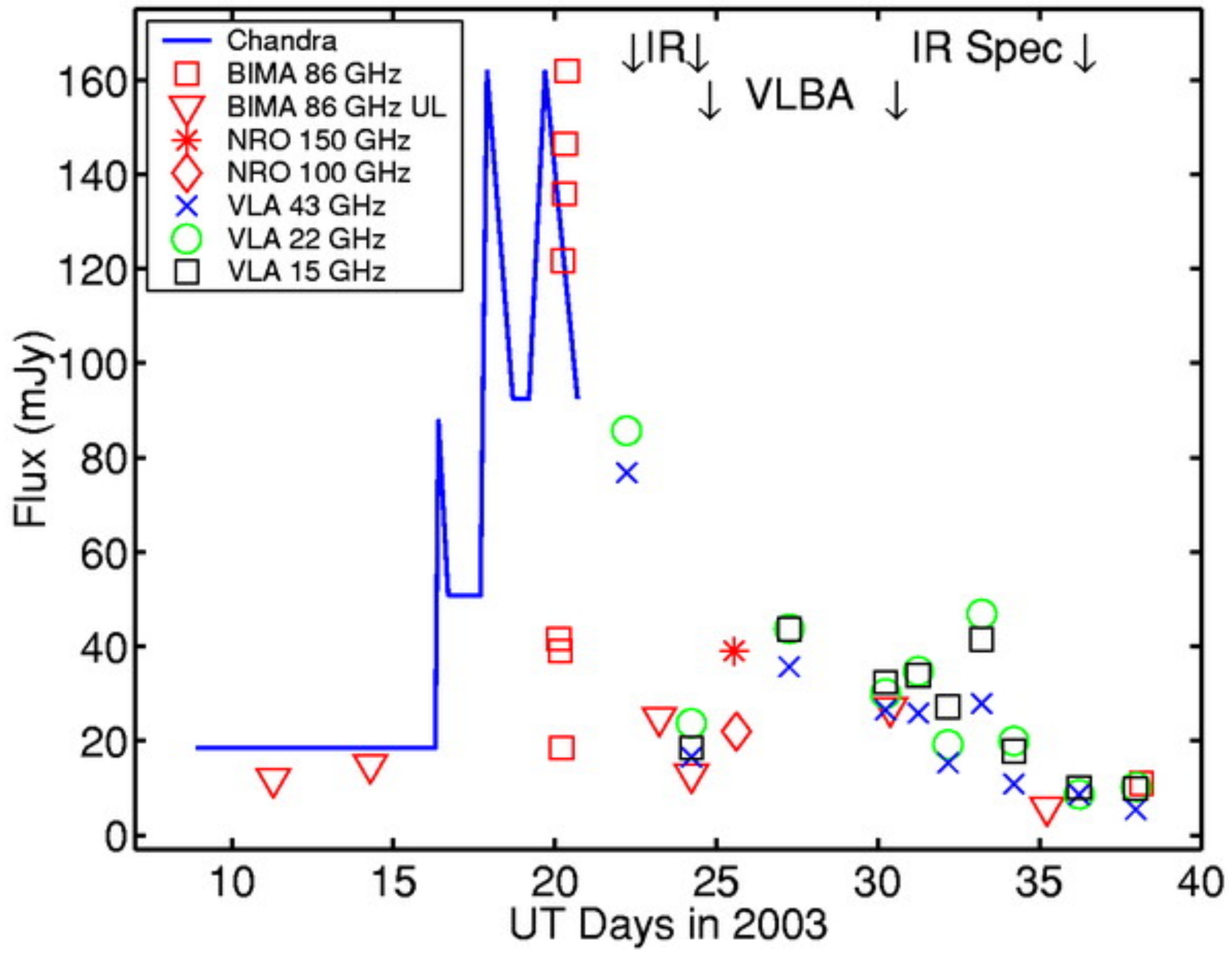


Kowalski et al. (2015)

- ➡Blue-optical flare spectral energy distribution has the shape of a black-body with $T_{BB} \sim 10^4$ K
- ➡Modelling this white light continuum enhancement requires a beam of accelerated electrons
- ➡Allred et al. (2005, 2006) showed difficulty in reproducing M dwarf white light flare with solar-like electron beam
- ➡Kowalski et al. (2015) showed that increasing the beam flux by two orders of magnitude from the largest beam flux seen in a solar flare can do the trick.

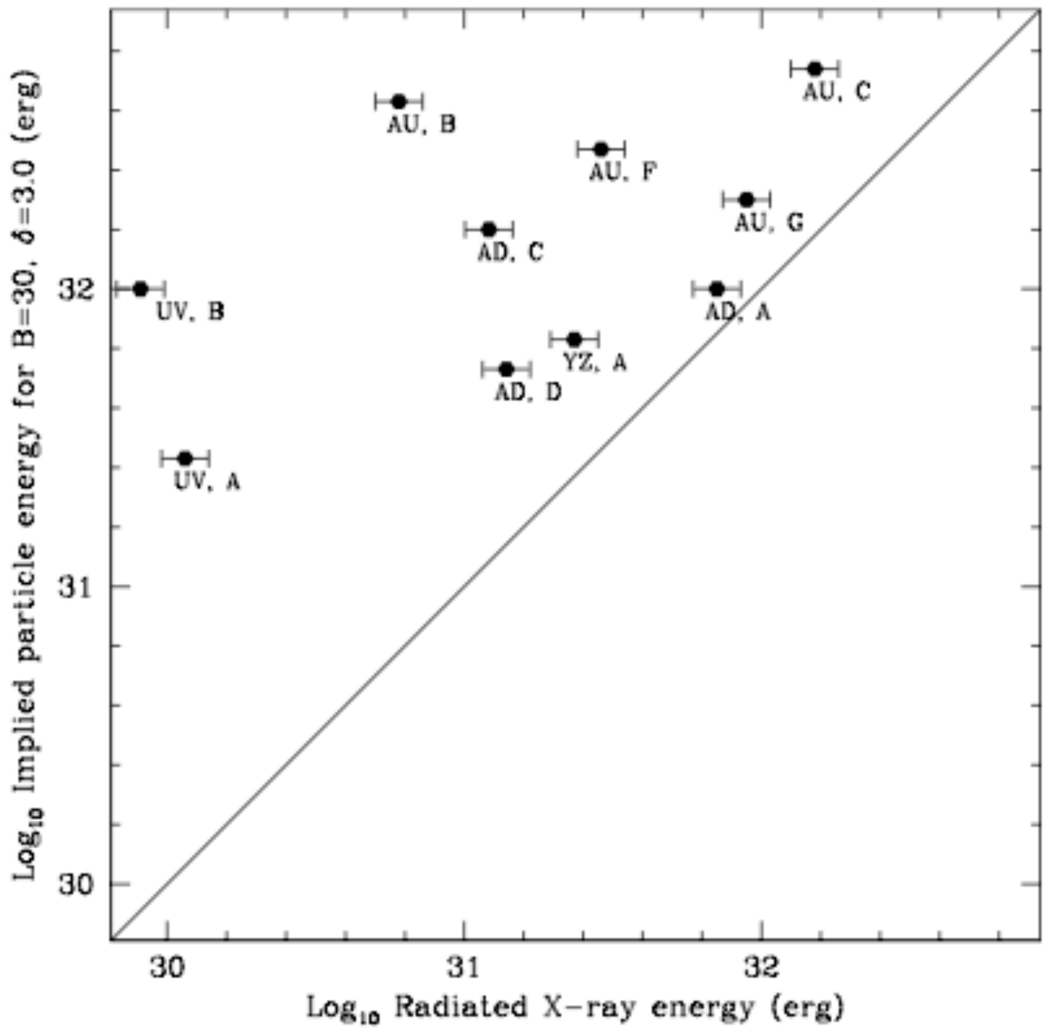
Open Questions Involving Multi-Wavelength Flare Observations

Time delays between different bands, how that relates to energization mechanisms



Bower et al. (2003)

Energy partition in different bandpasses/atmospheric layers, processes (particle acceleration, plasma heating)



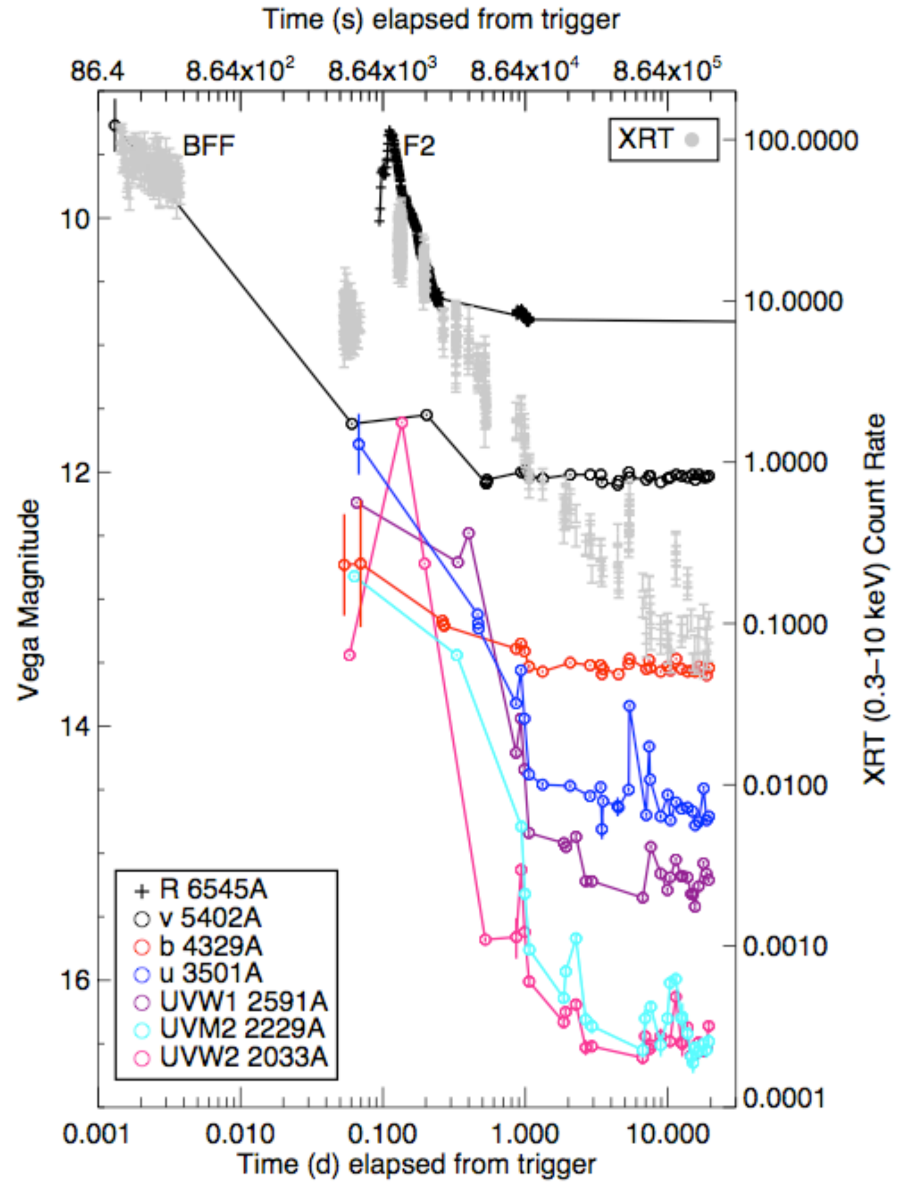
M dwarf flares

more energy in non thermal particles than in corona

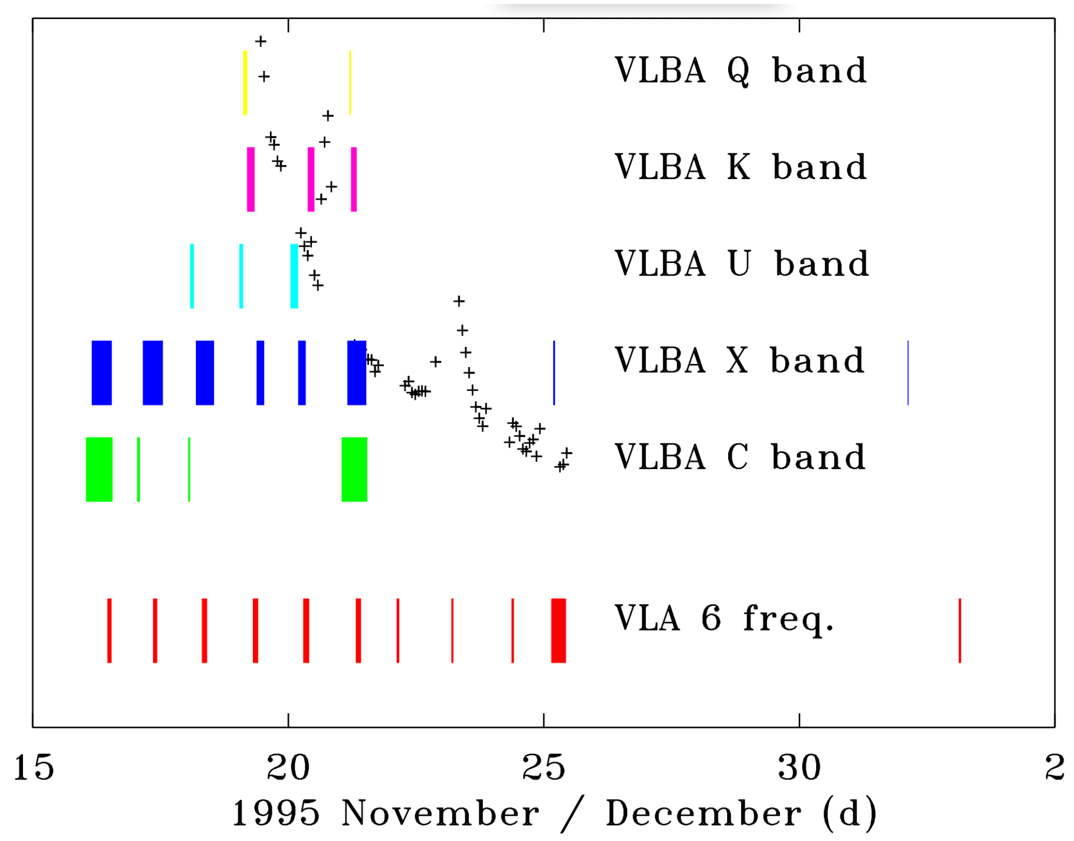
Smith et al. (2005)

Ways to Accomplish Multi-Wavelength Flare Observations

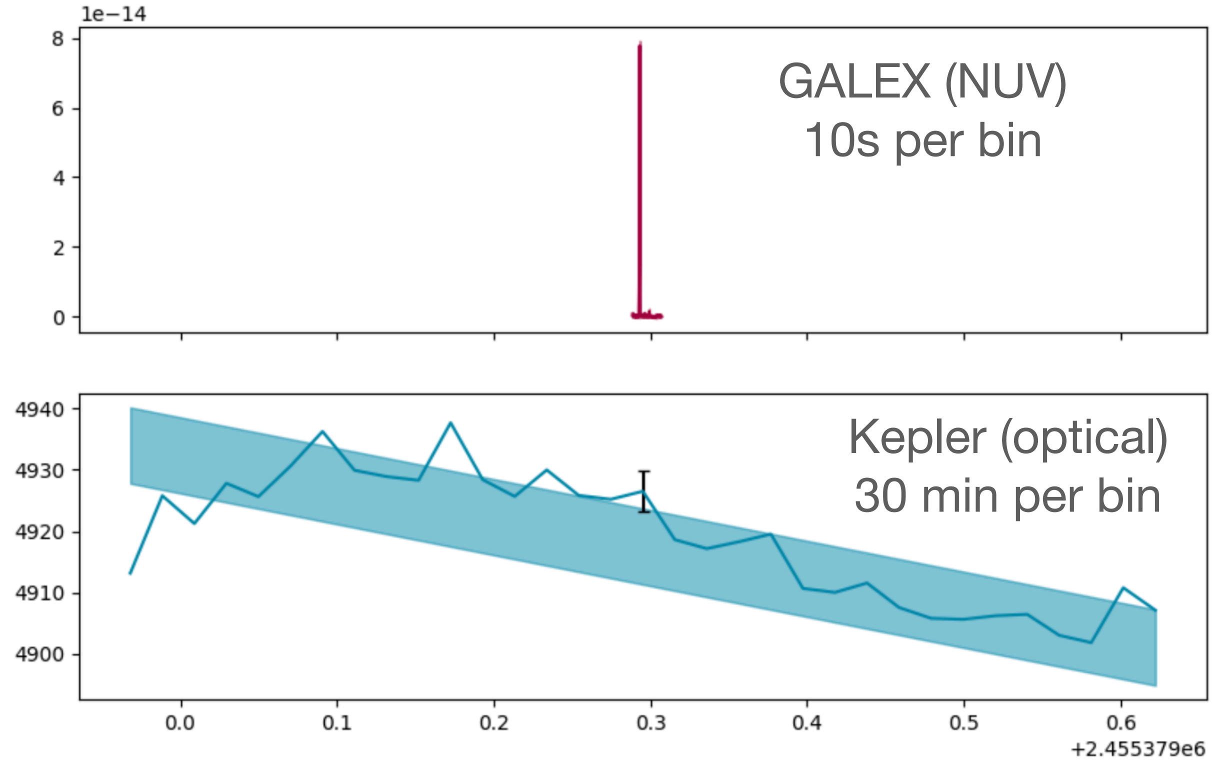
- One star at a time
  - Classical mode — write lots of proposals, coordinate observatories, cross fingers
  - Bias in stars which are targeted: the usual suspects (need high flaring rate)
  - Science results depend on flare timing, but can access impulsive phase
- Multiplexing
  - “stars by stars” — select regions with multiple flaring objects, e.g. star forming regions
  - Bias in stars which are targeted, these stars are further away so sensitivity effects
- Serendipitous
  - No prior coordination, “luck”
- Triggering (i.e. GRBs at 5 pc!)
  - Swift triggers provide hard X-ray, soft X-ray, UVO response + ground response
  - No intrinsic bias in stellar type; however, confirmation of usual suspects
  - Usually no information on impulsive phase as triggering happens at flare peak
  - Extreme flares
- Overlapping time domain surveys
  - Most general case, no intrinsic bias, potentially large #s of flares, but subject to the vagaries of how the initial data are set up/obtained



Osten et al. (2016) Swift trigger on DG CVn, followed up with ground-based optical + radio



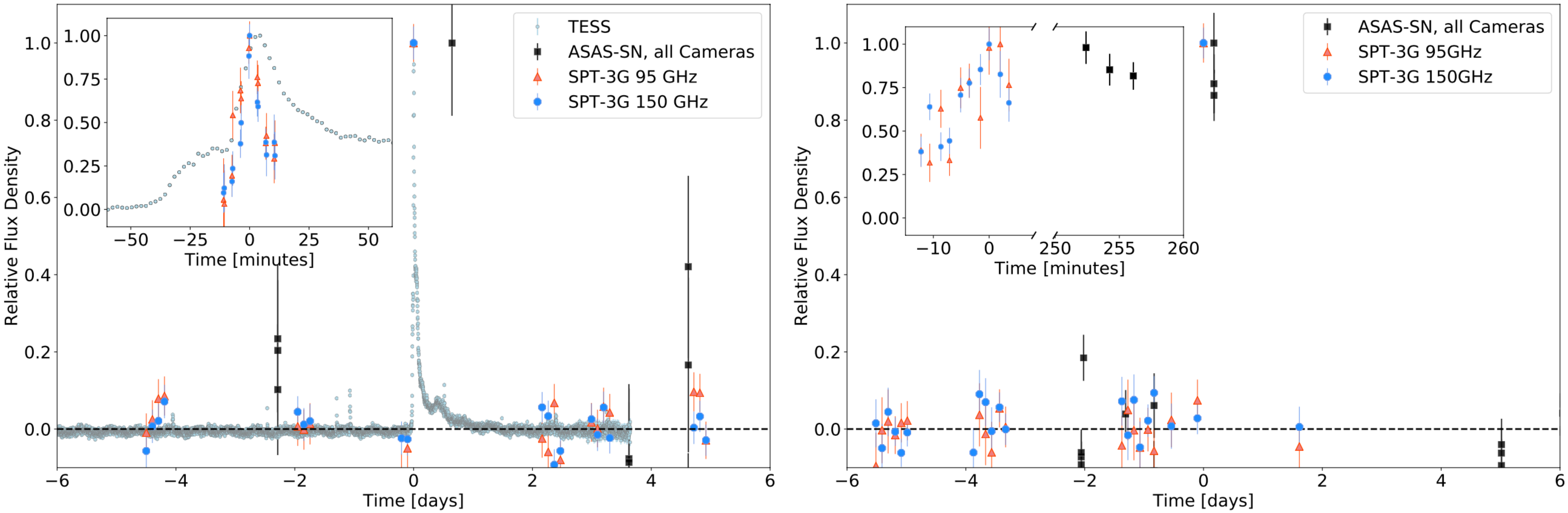
Example of serendipitous overlap between Extreme Ultraviolet Explorer (EUVE) and VLA+VLBA observations of a large flare



Brasseur et al. (in prep.) overlap between GALEX (NUV) survey of the main Kepler field, and Kepler (optical) observations

Thoughts on potential for CMB-S4 time-domain impact on stellar flare physics

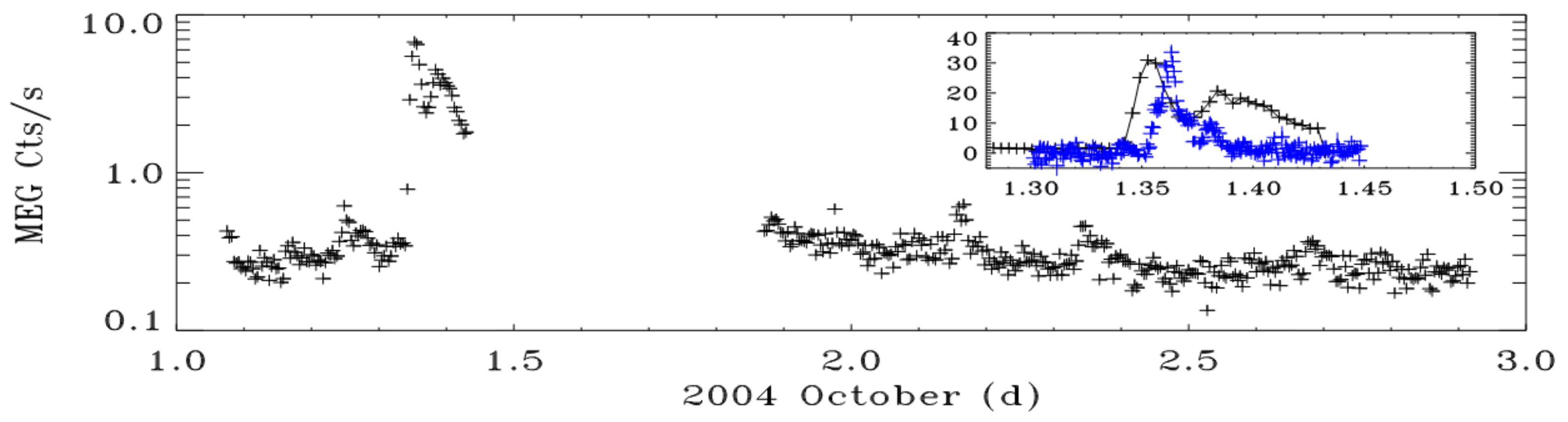
- Access to crucial wavelength region for exploring stellar particle acceleration, population statistics, fodder for future targeted investigations
- ACT and SPT initial results (Naess et al. 2020, Guns et al. 2021) seem to confirm the “usual suspects” for stars with enhanced magnetic activity



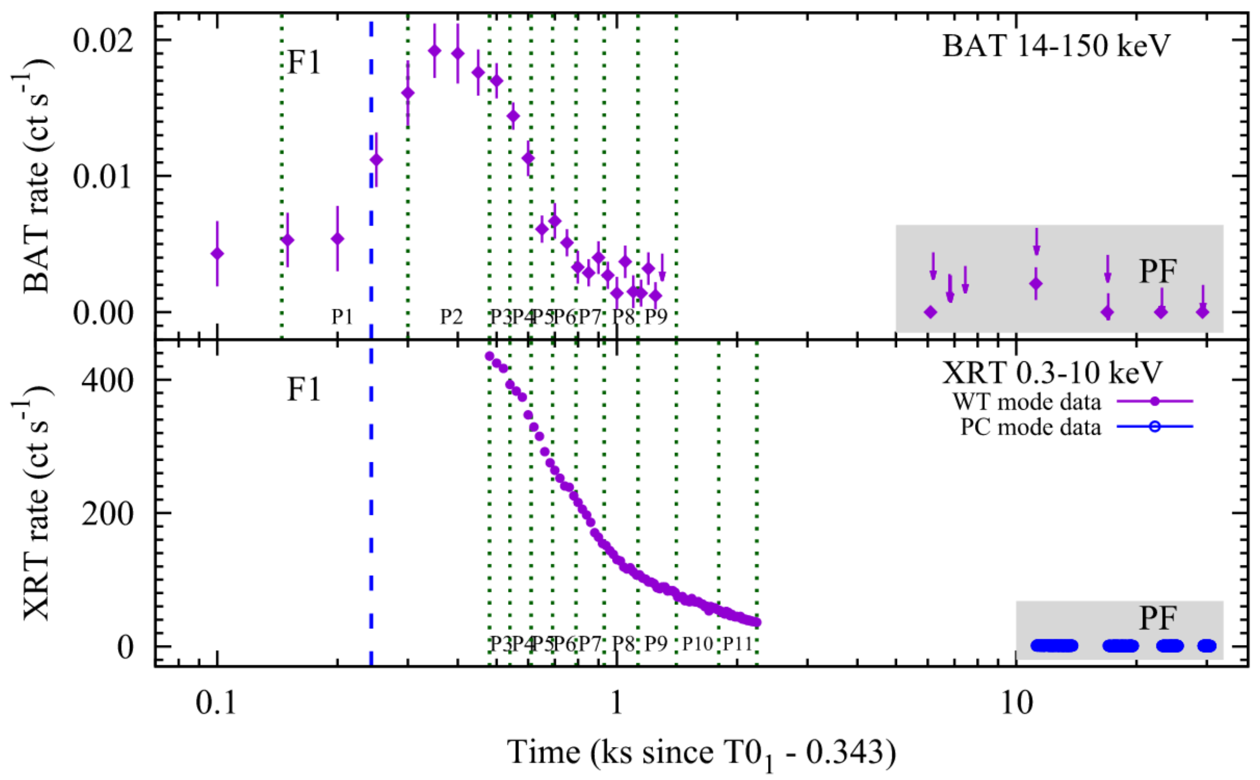
Guns et al. (2021)

Thoughts on potential for CMB-S4 time-domain impact on stellar flare physics

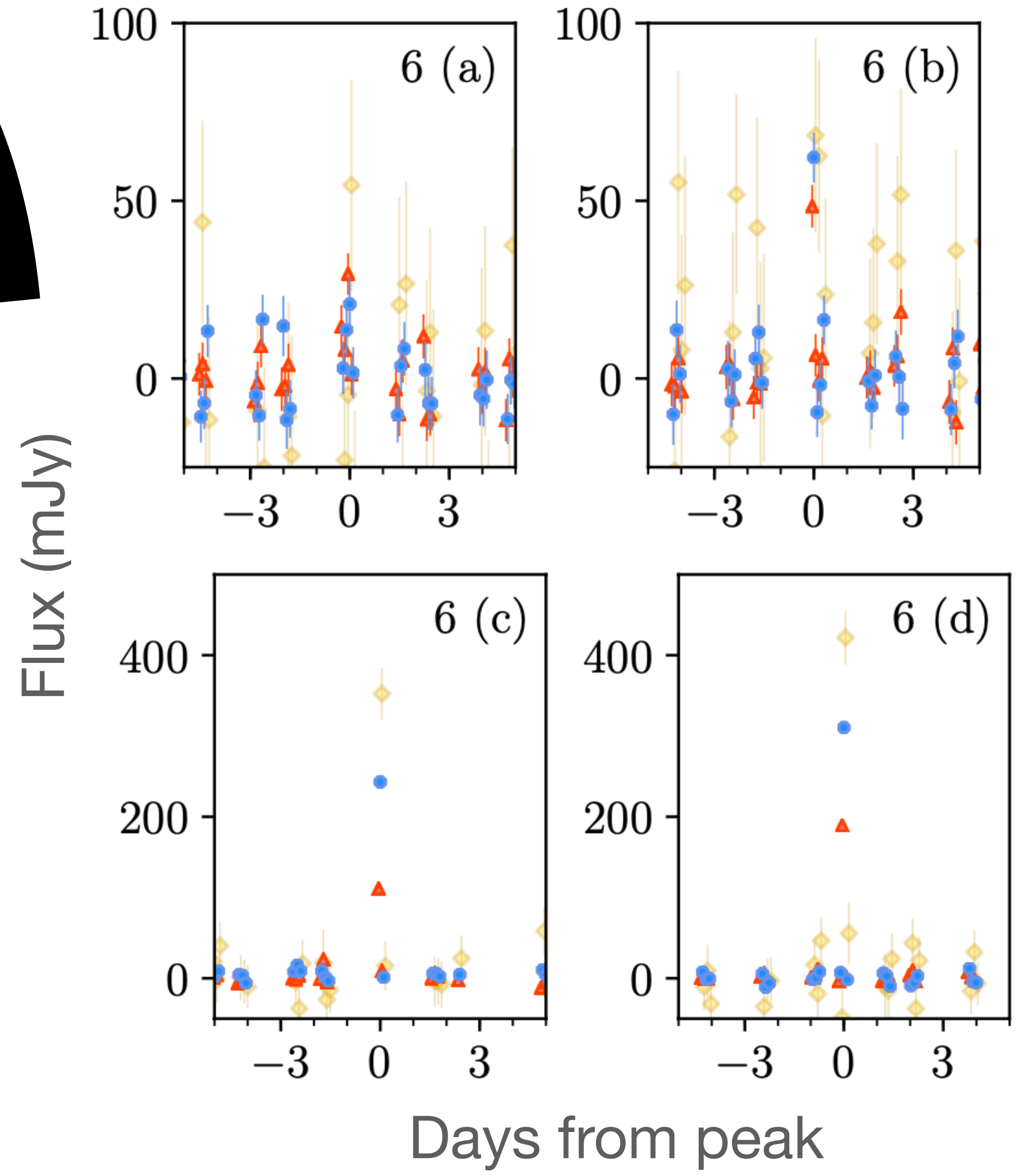
The “circle of life” for flare studies: case study of CC Eri



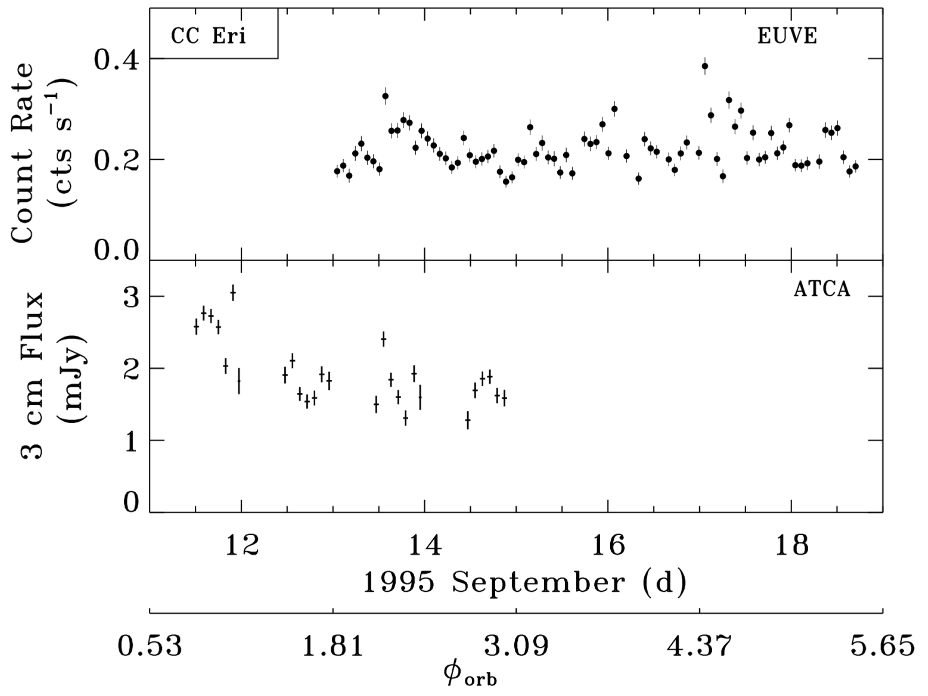
Budding et al. (2006)
coordinated observing campaign with
Chandra, VLA, ATCA, ZDI measurements



Karmakar et al. (2018)
Swift trigger



Guns et al. 2021
SPT time domain survey



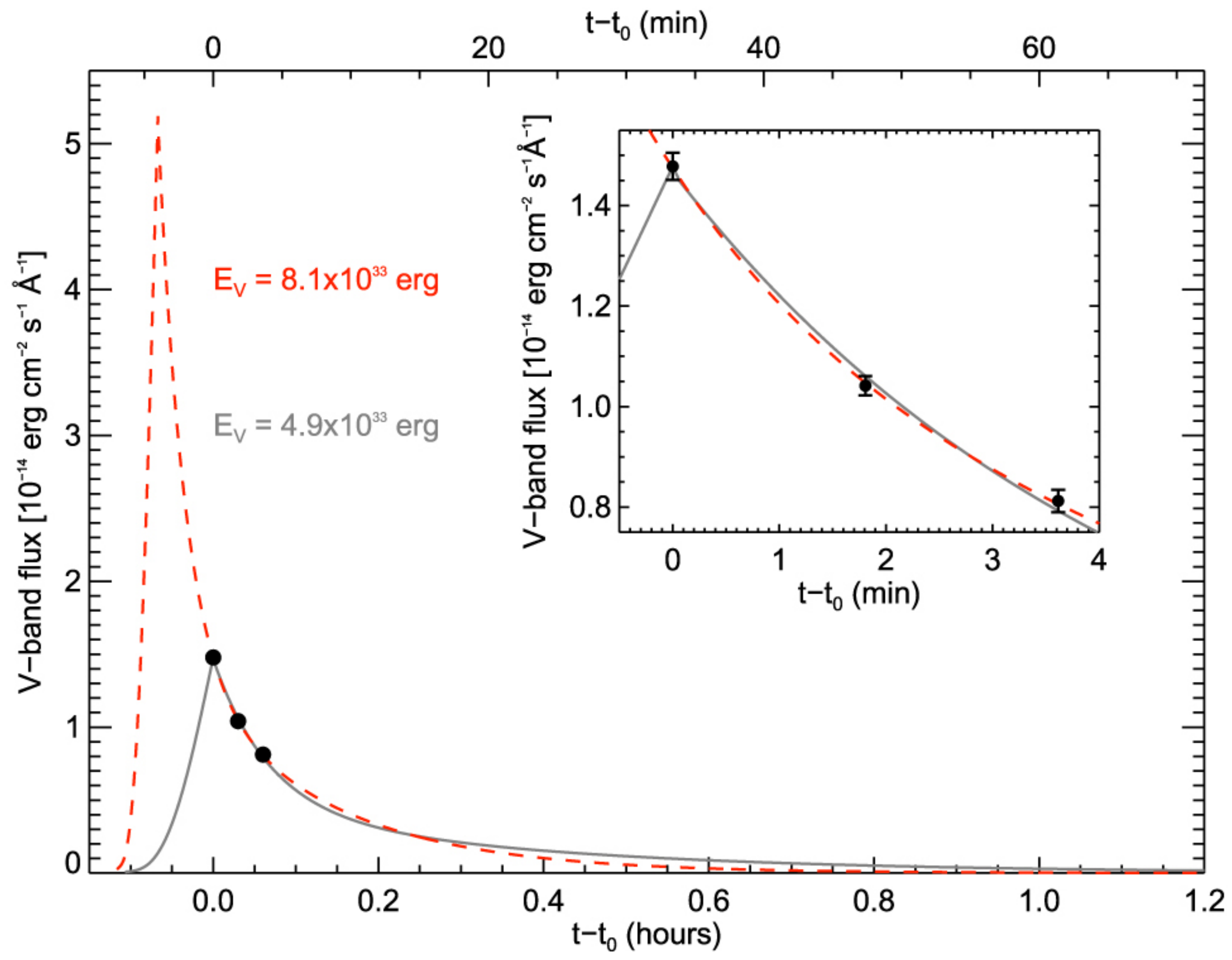
Osten et al. (2002)
coordinated observing campaign
with Extreme Ultraviolet Explorer,
ATCA measurements

future potential coordinated observations based on new results to study lower-energy flares

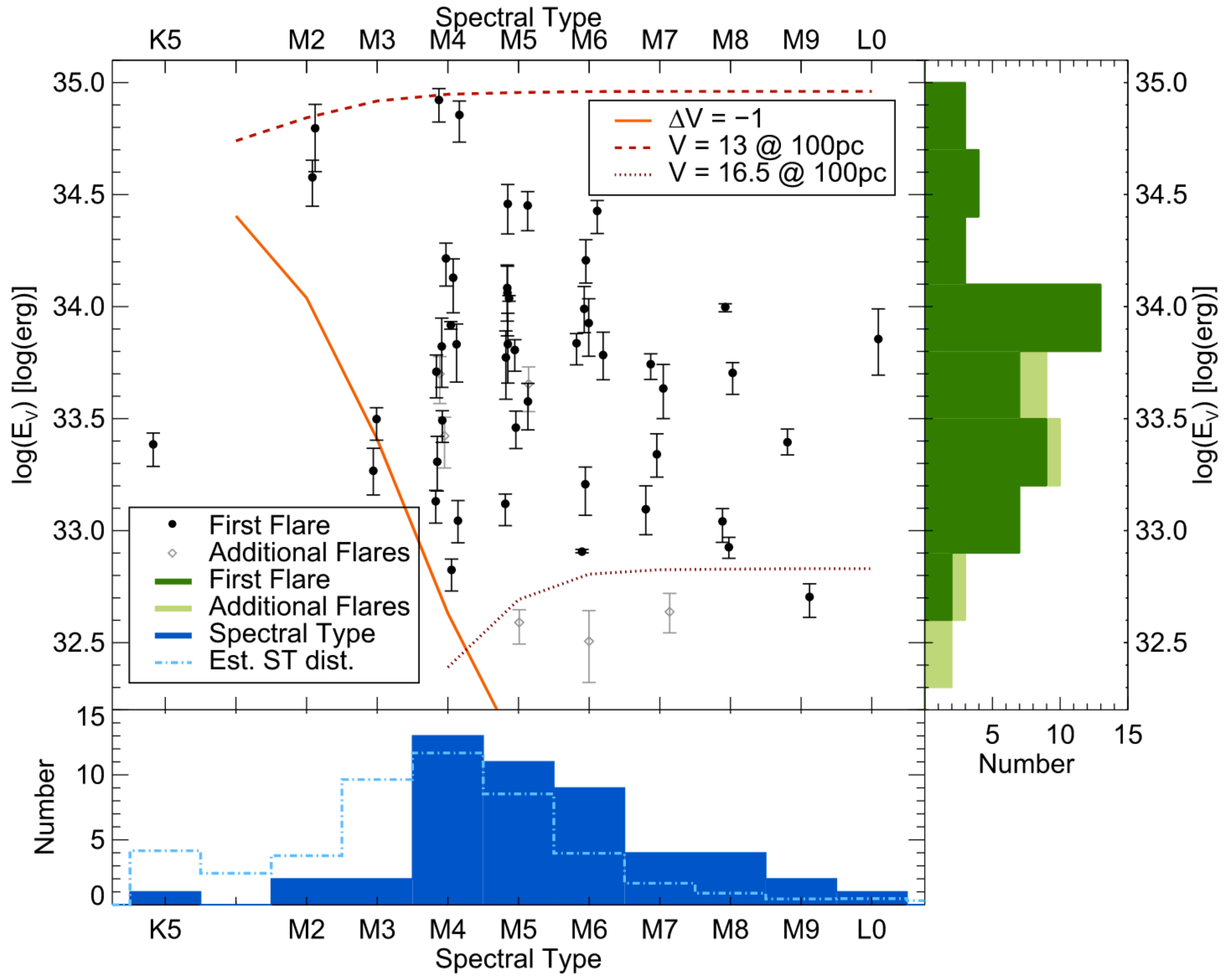
Overlapping Time Domain Studies

ASAS-SN as example precursor for extremes of stellar magnetic flares

ΔV with peak (observed) flux increase of -8 to -11 magnitudes, among the most energetic flares seen



Schmidt et al. (2016)



Schmidt et al. (2018)

Conclusion

Large potential to contribute to timely stellar investigations, largely utilizing the overlapping nature of future time-domain surveys (e.g. CMB-S4, Rubin)

- Need a combination of the following philosophies:
  - **Be Strategic** (select targets, arrange overlap as much as possible)
  - **Be Organized** (have follow-up capabilities arranged; piggyback on observational setup for more exotic time domain objects)
  - **Take What You Can Get** (luck of the draw, archival investigations)
- Can accomplish both study of individual flares, as well as overall statistics of flares and flaring stars